Theoretical study of signals from binary neutron star mergers(Digest_要約)

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Abstract

Binary neutron stars (NS–NSs) are among the strong gravitational-wave emitters in the Universe. They are one of the main targets of the second generation ground based gravitational-wave observatories such as Advanced LIGO, Advanced Vigro, and KAGRA. In this thesis, we systematically study NS–NS mergers based on numerical-relativity simulations. In particular, we focus on the dependence of the merger dynamics, gravitational waveforms, and mass ejection on equations of state (EOSs) of neutron-star matter. Then we make theoretical predictions for expected gravitational-wave and electromagnetic signals from NS–NS mergers within the uncertainties of the EOS of neutron-star matter. This research covers following topics:

(1) Tidal effects during a late inspiral stage of an NS–NS. We perform long-term numerical simulations of NS–NS inspirals ($\lesssim 10$ orbits) in order to explore tidal effects in a coalescing NS–NS, which reflect finite size of a neutron star in gravitational waves. We show that the numerical errors due to finite differencing dominate in our current numerical simulations. In order to obtain the physical waveforms, we perform the resolution-extrapolation of waveforms by analyzing numerical data with different grid resolutions. Comparing the extrapolated numerical and analytical waveforms, we find the strong tidal effects in our numerical simulations in a last few orbits. Here the analytical waveforms are computed by a post-3.5 Newtonian formalism or effective one body formalism. Both the formalisms include tidal effects as a perturbation. We also find that the extrapolated-numerical waveforms obtained by our current simulations can not be used as template waveforms due to numerical errors. Therefore we need higher-accuracy simulations in order to construct end-to-end waveforms of NS–NS mergers.

(2) Post-merger dynamics and resulting gravitational waveforms. Recent discoveries of heavy pulsars indicate that the EOS of neutron-star matter is sufficiently stiff. Based on such a stiff EOS, a massive neutron star is likely to be formed after an NS–NS merger. We study the first outcome of NS–NS mergers for several masses and EOSs. We find that a massive neutron star mostly survives for an NS–NS merger with the total mass range from $2.6M_{\odot}$ to $2.8M_{\odot}$, irrespective of the EOS. On the other hand, their final fates depend on the EOS and the total mass. These results encourage us to take into account the existence of a remnant massive neutron star, when we study the central engine of gamma-ray bursts (GRBs) based on the compact binary merger hypothesis.

These remnant massive neutron stars can be strong gravitational-wave emitters. Gravitational waveforms from massive neutron stars are analyzed. As a result, we find the correlation between the characteristic frequency of the gravitational waves and neutron star radii. Furthermore, we attempt to construct a phenomenological-waveform model of the post-merger waveforms, which can describe numerical waveforms with the mismatch of $\lesssim 10\%$. Such a phenomenological modeling of numerical waveforms will be useful for gravitational-wave data analysis.

(3) Mass ejection from an NS–NS merger. A fraction of material is expected to be dynamically ejected at the merger. We study dynamical mass ejection from an NS–NS merger based on numerical relativity-simulations. In order to compute dynamics of unbound material, a relatively wide computational domain is employed. As a result, we find that ejecta mass is in the range of 10^{-4}–$10^{-2}M_{\odot}$ and the ejecta velocity is in the range of 0.1–$0.5c$, for the various total masses, mass ratios, and EOSs. Remarkably, we find that the amount of ejecta is large for the case of hypermassive neutron star (HMNS) formation. As long as a long-lived HMNS is formed, the following properties can be found: (i) For a given EOS, the ejecta mass increases with total mass of an NS–NS. (ii) For a given mass, an NS–NS merger with a softer EOS produces a larger amount of ejecta. (iii) Ejecta have a spheroidal shape rather than a disk-like shape. These features of mass ejection of NS–NS mergers will be helpful to investigate electromagnetic signals from the NS–NS merger ejecta. Furthermore, a spheroidal shape of ejecta indicates that a relativistic jet which may produce a GRB is inevitable to interact with ejecta. This will be an important subject in a context of production of short GRBs.

(4) A kilonova candidate associated with the short GRB 130603B. A near-infrared excess was observed at 9 days after the *Swift* short GRB 130603B by *Hubble Space Telescope*. This excess can be explained as an r-process kilonova/macronova emission produced either by an NS–NS merger or a black hole–neutron star merger. We explore the possible progenitor model based on numerical-relativity and radiative transfer simulations. As a result, we show that NS–NS merger models with soft EOSs and black hole–neutron star merger models with stiff EOSs are the possible progenitor model of the short GRB 130603B. This result support the fact that a kilonova/macronova will be an observable electromagnetic counterpart to a gravitational-wave signal from a compact binary merger.